

Using Oceanographic Linkages to Guide Marine Protected Area Network Design

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Abstract

Marine protected areas (MPAs) will be most effective when established as networks linked through larval dispersal. Larval import will provide new individuals to protected populations, and larval export will supply individuals to surrounding populations. Larval dispersal trajectories therefore constitute one important element of network design.

We used drift cards to infer larval transport by surface currents in the San Juan Archipelago (SJA) and Northwest Straits region of Washington State. We released 6400 cards from 16 sites within the SJA from April through September, 1999. Nearly 40% of these were recovered and reported to us. Throughout the region, cards tended to accumulate on a relatively small proportion of the total shoreline. For example, within the SJA, approximately 70% of the cards accumulated on only 15% of the shoreline. The spatial distribution of recoveries suggests that sites within the SJA are tightly linked with each other and with several other sites around the eastern basin of the Strait of Juan de Fuca. In particular, the southwest shore of Lopez Island, Dungeness Spit, the northwest shore of Whidbey Island, and the Victoria area all are likely to sustain high levels of larval import, indicating their potential importance in regional MPA network design.

Introduction

Principles and criteria for marine protected area (MPA) design are developing rapidly. For example, it is now generally agreed that to be effective, populations within MPAs must be self-sustaining and capable of supplying larvae to other protected and unprotected populations (Carr and Reed 1992; Ballantine 1997; Starr 1998; Sladek Nowlis and Yoklavich 1998; Carr and Raimondi 1998). Therefore, both larval supply and the degree of linkage between sites will be important in the establishment of effective MPA networks. Larval supply influences recruitment rates and is an important determinant of local population sustainability for populations in which recruitment is limiting. Linkages between sites facilitate larval exchange between protected areas, enhance persistence and growth of populations within networks of marine protected areas, and guard against losses due to stochastic processes. The importance of larval linkages increases as population size in the unprotected areas declines and as the size of the unprotected area increases relative to that of protected areas. Thus, linkages will be especially important where fishing pressure in unprotected areas is high, and in areas where a relatively small proportion of the habitat is protected.

Larvae of many species of interest (e.g., rockfish, echinoderm, and decapod species) spend long periods in the plankton (Allison and others 1998; Strathmann 1987). Consequently, their recruitment into nearshore habitats will depend on larval behavior and on local and regional surface circulation patterns. For example, researchers in northern California have found the recruitment of crabs and urchins to be dependent on mesoscale oceanographic processes that tend to collect larvae in offshore pools during periods of upwelling (Wing and others 1995 a,b). Larvae return to shore during periods of upwelling relaxation. These findings have led to the suggestion that marine harvest refugia in the region be positioned to take advantage of the circulation patterns that return larvae to protected nearshore habitats (Morgan and Botsford 1998). Thus, the underlying regional oceanographic features that entrain and redistribute larvae constitute one important

criterion upon which MPA networks can be based; and the identification of potential linkages between sites represents a first critical step in MPA network design.

The San Juan Archipelago

The San Juan Archipelago is bordered by Rosario Strait to the east, Haro Strait to the north and west, and the Strait of Juan de Fuca (SJDF) to the west and south. The archipelago includes hundreds of small islands and several larger islands, the largest of which (San Juan and Orcas) exceed 50 sq. mi. The islands are characterized by steep, rocky shores interspersed with cobble or sand beaches of shallower aspect. The subtidal topography is typically steep, reaching depths of more than 100 m within 1/2 mile of shore. Tidal currents through the SJA can be extreme, reaching 6 knots in some areas. The SJA occupies the northeastern Northwest Straits (NS), and much of the local oceanography is driven by regional circulation patterns within the NS, described below.

The Northwest Straits

The Northwest Straits region includes the waters of the SJDF and northern Puget Sound from the Canadian border to the southern tip of Whidbey Island. It is characterized by a predominantly estuarine circulation (Thomson 1981) driven in large part by outflows from the Fraser River and from lower Puget Sound. Consequently, the long-term average near-surface flow is seaward (Thomson 1981; Holbrook and others 1980), with an estimated speed through the SJDF of 6 km/day (Pashinski and Charnell 1979). This circulation pattern suggests that larvae could be supplied to the NS from the Strait of Georgia and from lower Puget Sound, and that a substantial proportion of the larvae produced in the NS could be exported to the Pacific Ocean via the SJDF. However, periodic flow reversals are known to occur, during which oceanic surface waters are injected considerable distances into the NS. These flow reversals often are associated with winter storm events lasting approximately 1 to 10 days and recur at infrequent intervals throughout the year (Thomson 1981; Holbrook and Halpern 1982; Ebbesmeyer and others 1995). Intrusions of oceanic water may provide an important source of larvae for recruitment to local populations. For example, Dinnel and others (1993) distinguished three cohorts of juvenile Dungeness crab in Puget Sound in 1988. They hypothesized that two of these originated from local parental stocks, but that the third represented an intrusion of larvae from outer coast populations associated with an intermittent flow reversal.

Superimposed on this estuarine flow regime are tidal currents that can reach speeds of several knots. Tidal flows can cause vigorous vertical mixing (Griffin and LeBlond 1990; LeBlond and others 1994), and can create tidal eddies that entrain and redistribute buoyant particles, including larvae (Ebbesmeyer and others 1991). Thus, the formation and dissipation of tidal eddies may represent a feature of considerable importance to larval dispersal and delivery within the NS system.

An additional feature of potential importance is the presence of sills at the north, south, and western entrances to the eastern basin of the SJDF. These sills cause entrainment and vertical mixing of surface waters (LeBlond and others 1994; Ebbesmeyer and Barnes 1980), potentially reducing the export of locally produced larvae to the Pacific Ocean. Thus, although the average net flow through the NS straits is seaward, periodic flow reversals, tidal eddies, and mixing at sills all may act to retain and redistribute locally produced larvae within the system.

Methods and Materials

Drift cards were used to describe coarse surface circulation patterns and to infer larval transport within the SJA and eastern basin of the SJDF. Drift cards were made of mahogany plywood measuring 10 x 15 x 0.2 cm. Cards were painted orange and printed with contact information for reporting recoveries. Fifty cards were released from each of 16 sites at approximately 3-week intervals from April through September 1999 (Tables 1 and 2). The recovery site and date were recorded for each card reported. Recoveries were assigned to 1-mile segments of shoreline and transformed to GIS coordinates for purposes of mapping.

Drift cards and other passive drifters have been used repeatedly by oceanographers to describe surface circulation, but they have rarely been used to address physical/biological coupling. In this study, we used drift cards to infer the potential for larval linkages between sites and to identify the approximate scales of

local and regional linkage. Drift cards are a better proxy for particles (including larvae) traveling in the surface layer than for those traveling in deeper layers. Surface-borne larvae include buoyant larvae, late-stage larvae of intertidal organisms, and larvae traveling with kelp mats and other floating material. One shortcoming of the drift card method is that it provides an imperfect model for larval transport in deeper portions of the surface layer. However, the vigorous tidal mixing characteristic of the SJA reduces stratification and potentially reduces the associated discrepancies between transport in the surface microlayer and in sub-surface waters. A second shortcoming of the method is that it does not account for larval behavior. Therefore, larvae that are capable of exhibiting strong behavior will be distributed differently than passive drifters. Third, the habitats in which drift cards strand are typically low-aspect beaches of medium to low energy. These habitats are not suitable for some species (e.g., adult rockfish), and larvae of such species will not recruit successfully to these sites. Even so, the drift card method is useful because it describes an envelope of potential larval dispersal that will be modified by taxon-specific behavior and habitat availability. For the purposes of MPA siting, drift card studies are best combined with empirical evidence of larval recruitment and with characterization of suitable habitat.

Table 1. Summary of Releases

Release Number	Release Date	Total Cards Released
1	04/08/99	800
2	04/27/99	800
3	05/20/99	800
4	06/10/99	800
5	07/06/99	800
6	07/29/99	800
7	08/24/99	800
8	09/20/00	800

Table 2. Release sites, site codes, and MPA status (Y = existing MPA, N = no existing MPA)

Release Site	Site Code	MPA?
Charles Island	A	Y
Point Colville	B	N
James Island	C	N
Frost Island	D	N
Obstruction Pass	E	N
Point Lawrence	F	Y
Bare Island	G	Y
Gull Rock	H	Y
Turn Point	J	N
Kellett Bluff	K	Y
Limekiln	L	Y
Pile Point	M	Y
Pear Point	N	N
Orcas Landing	P	N
Bell Island	Q	Y
Point Caution	R	Y

Results

Thirty-nine percent of the cards released were recovered and reported by December 1999. Overall, 95% of the recoveries were made in the eastern basin of the SJDF, 3% in the western basin, and 2% on the outer coasts of Washington, Oregon, and British Columbia. Fifty-seven percent of the total recoveries were made within the SJA. Cards were reported from as far south as Florence, OR and as far north as Kayak Island, AK.

Recoveries are plotted by release site in Figures 1-16. These figures reveal that cards released from sites on the east side of the SJA (sites B-F) tended to travel east more frequently than cards released from other sites. Cards released from sites in Haro Strait (G, J-M), and especially the northern part of Haro Strait (G, J, and K), tended to travel south and west, with a large proportion of these stranding around Victoria and on Dungeness Spit. Interestingly, cards from all release sites were recovered from shores within the Middle and San Juan Channels.

Strandings were disproportionately frequent in some areas (Figure 17). For example, five areas (Neck Point on Shaw Island, the southwest shores of Lopez and San Juan Islands, the outer shores of Victoria, the north shore of the Dungeness Spit, and the northwest shore of Whidbey Island) accounted for 33% of all recoveries. These areas appear to function as major collection zones for buoyant particles.

The spatial pattern of recoveries generally can be explained by regional surface current patterns that have been described from previous drift card studies in the SJDF and Puget Sound (Ebbesmeyer and others 1991). This study represents the first major release of drift cards within the SJA and the first description of large numbers of cards entering the SJDF from the north. With one exception (Neck Point on Shaw Island), the pattern of recoveries observed in this study was consistent with results from previous studies performed in the SJDF.

Cards accumulate on Dungeness Spit by the combined action of a current running from Ediz Hook to Dungeness Spit and strong tidal eddies that develop on the ebb tide in the lee of Dungeness Spit. Accumulations in three other areas are caused by tidal eddies that develop on ebb tides. Cards are deposited between Port Townsend and Discovery Bay by the ebb tidal eddy issuing from Admiralty Inlet. Accumulations on the southern shores of Lopez and San Juan Islands result from ebb tidal eddies formed in the southern lee of the SJA. Accumulations on the outer shores of Victoria result from an ebb tidal eddy formed by effluent from Haro Strait. Accumulations on the northwestern shore of Whidbey Island may be due to the general southerly current running from Rosario Strait to Admiralty Inlet. Accumulations along Neck Point on Shaw Island have not previously been described; however, these likely are the result of tidal eddies formed by flows through San Juan Channel and Wasp Passage.

Few cards were recovered within Puget Sound. The Sound drains into the SJDF through Deception Pass and Admiralty Inlet. In both, strong average currents set from Puget Sound into the SJDF. Consequently, few cards are transported upstream into Puget Sound. In this study, only three cards were found inside Deception Pass, and very few were found inside Admiralty Inlet.

The power of tidal eddies and other oceanographic features to accumulate buoyant particles is demonstrated by the fact that 70% of recoveries were made on only 15% of the shorelines within the region. This result is similar to those from previous studies (Ebbesmeyer and others 1991), and indicates that currents concentrate buoyant particles 4 to 5 times greater than expected from a uniform distribution. Tidal currents and eddies represent persistent major physical features of the local environment that likely have important consequences for marine organisms and populations within the region.

Drift card studies have been criticized as biased due to variable frequency of visitation between beaches. While it is true that some beaches in the region are more accessible and receive higher rates of visitation than others, beachcombers are active throughout the region in all months (CCE, pers. obs.). Clearly, visitation rates alone cannot explain the distribution of recoveries. For example, Limekiln State Park on San Juan Island is among the most frequently visited state parks in Washington. However, recoveries from the area surrounding Limekiln were far fewer than from other areas such as Shaw Island and the southwest

shore of Lopez Island, both of which receive far less visitation. Visitation rates will influence how quickly a card is recovered after stranding, and may partially explain some of the finer-scale differences in rates of recovery. For example, along Dungeness Spit, most cards were recovered from the base of the spit, which receives higher rates of visitation than other parts of the spit. Even so, recovery patterns at the regional scale correspond more closely with oceanographic features than with visitation rates.

Discussion

In general, these results indicate a relatively high degree of linkage between sites within the SJA. This is best seen from the distribution of strandings within the San Juan and Middle Channels, where cards from all release sites were found. In addition, cards released from Haro Strait were recovered in Rosario Strait, and cards released in Rosario Strait were recovered in Haro Strait. Thus, sites along these three main channels are not isolated from one another.

The distribution of recoveries with the SJA implies the existence of a counter-clockwise circulation around the archipelago. Although the data presented here are not sufficient to resolve this pattern, they imply that sites along Rosario Strait will export larvae to Haro Strait and the San Juan and Middle Channels. Sites along Haro Strait will export larvae to the San Juan and Middle Channels. Sites within and the San Juan and Middle Channels appear to function more often as collection zones than as sources.

Further, the SJA appears to be tightly linked via export to other areas around the eastern basin of the SJDF, especially Victoria, Dungeness Spit, and the northwest shore of Whidbey Island. The data reported here do not allow us to estimate import to the SJA from these areas, but other data (e.g., Pashinski and Charnell 1979; Ebbesmeyer and Coomes 1993; Crone and others 1998) indicate that the southern end of the SJA and the Middle Channel act as collection zones for particles released from sites to the south and west of the archipelago. Thus, larval import to the SJA from the vicinities of Dungeness Spit, northwest Whidbey Island, and Victoria appears likely.

Spatial and temporal stranding patterns indicate that the eastern basin of the SJDF may function as a reservoir for larvae entrained at or near the surface. Ebbesmeyer and others (1991) have shown that several tidally induced eddies consistently form along certain shores within the eastern basin. These eddies are in large part responsible for the deposition of buoyant materials on the shores of Dungeness Spit, the south end of Lopez Island, and Victoria. However, eddy formation and dissipation may also act to entrain and transport buoyant particles (including larvae) from nearshore areas where eddies form to the center of the eastern basin, where eddies dissipate. Thus, larvae produced near shore could be transported to and collected in the eastern basin by the consistent formation and dissipation of tidally induced eddies. These larvae might then be redistributed to shores around the eastern basin by the combined effects of wind, tidal currents, and internal waves (Shanks and Wright 1987). This model requires explicit testing before it is assumed to be correct. However, if the model proves to be correct, then the process of eddy formation and dissipation may provide an important mechanism by which locally produced larvae are retained and redistributed within the SJDF.

The results of this study have implications for the design of MPA networks within the region. First, regarding the existing MPAs within the SJA, this study implies that linkages exist between Rosario and Haro Straits and the San Juan and Middle Channels. Thus, existing MPAs in the SJA potentially are capable supplying larvae to and receiving larvae from sites throughout the archipelago, and therefore are capable of functioning as a local network.

Second, the observed linkages between the SJA and Victoria, Dungeness Spit, and the northwest shore of Whidbey Island indicate that these areas have potential value in the formation a regional MPA network. Larvae of many species are likely to be exchanged between these sites on temporal scales appropriate to conservation efforts.

Third, the potential for the eastern basin of the SJDF to function as a reservoir in which larvae collect before their eventual redistribution to regional shorelines has important implications for network design. If this model is shown to be correct, then MPAs could be positioned around the eastern basin to optimize the

supply of larvae to the pool. This can be accomplished by protecting the areas where tidal eddies form. In addition, shorelines around the eastern basin that provide suitable habitat for recruitment could be included in an MPA network. Finally, some form of protection for the eastern basin itself might be considered. The eastern basin is the site of heavy vessel traffic *en route* to the ports of Vancouver, Everett, and Seattle, and the risk of an accidental collision or spill is not trivial. In addition, the eastern basin likely concentrates surface-borne pollutants by the same mechanisms and in the same places that larvae are concentrated. Therefore, protection of water quality in the eastern basin itself could be critical to preserving its function as a larval reservoir.

Acknowledgements

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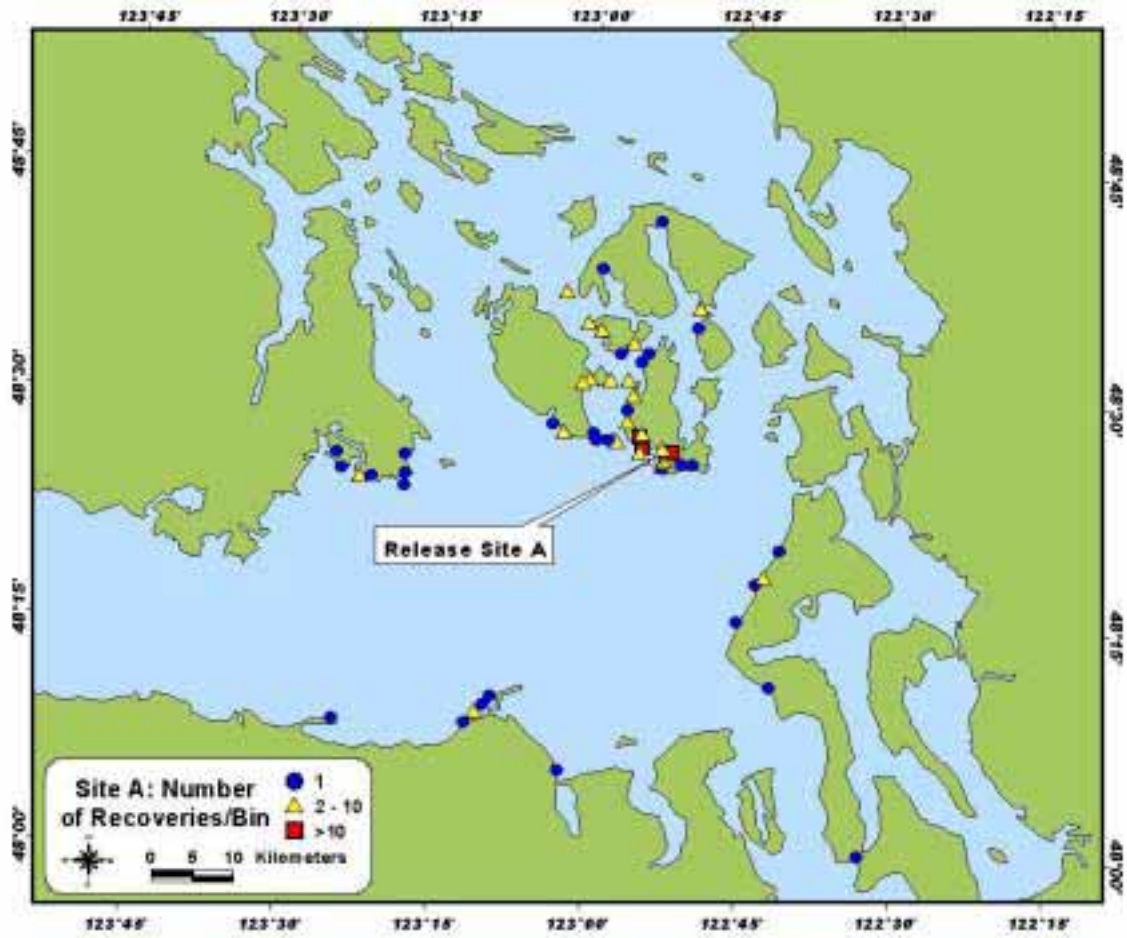


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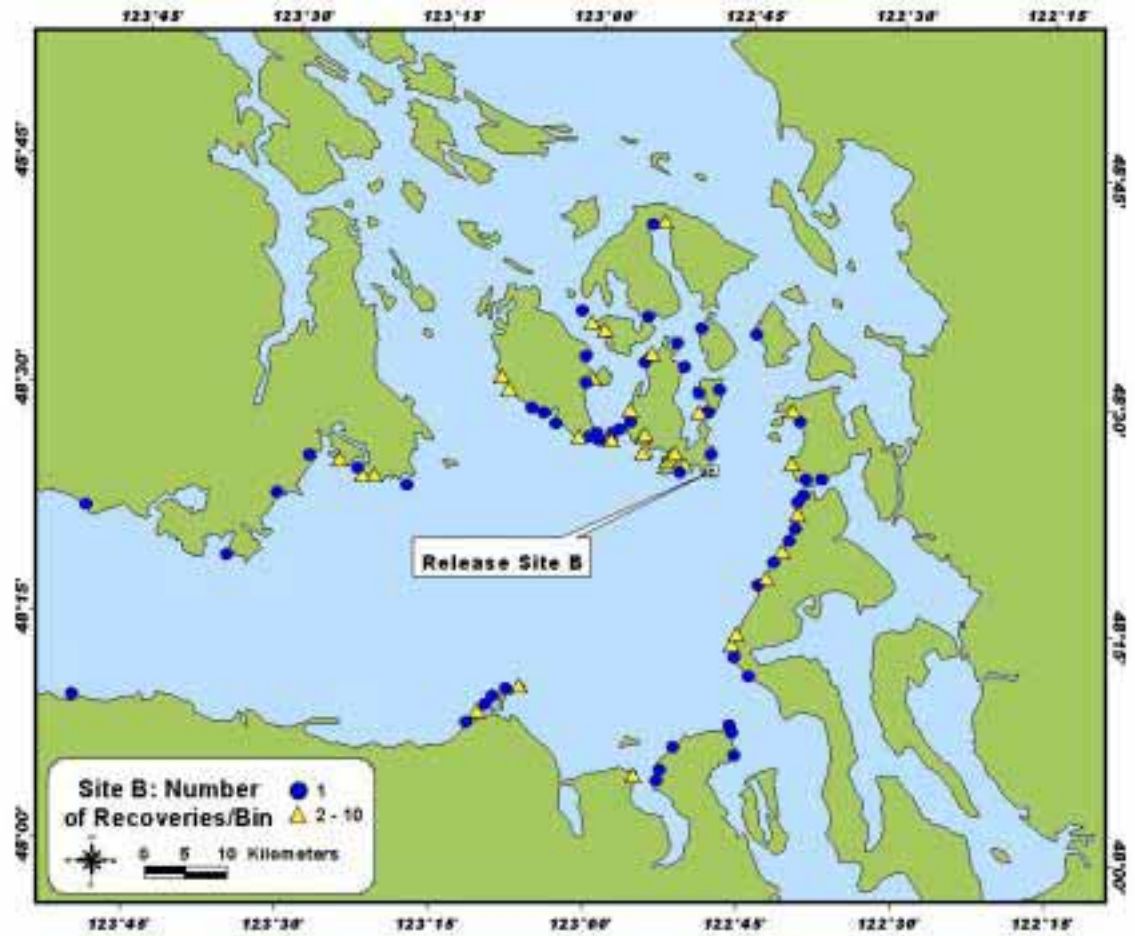


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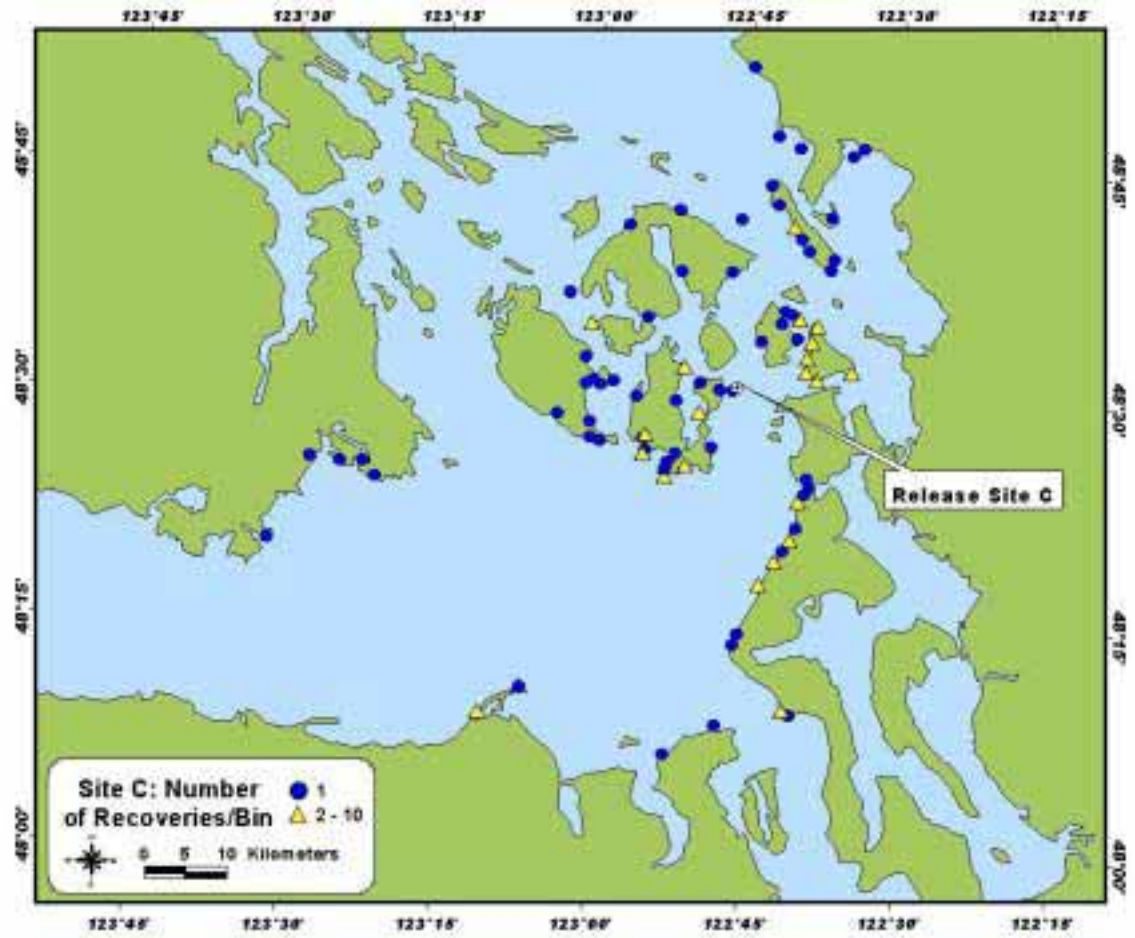


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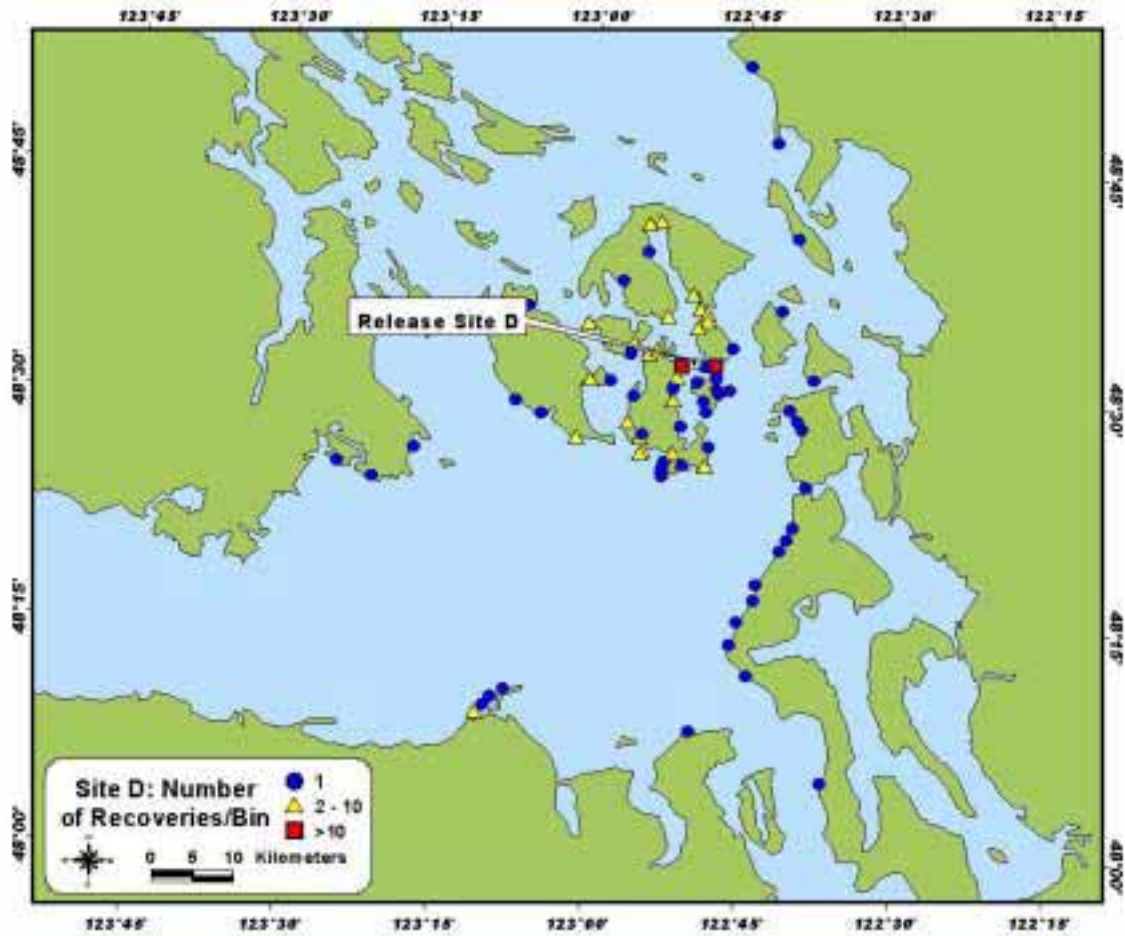


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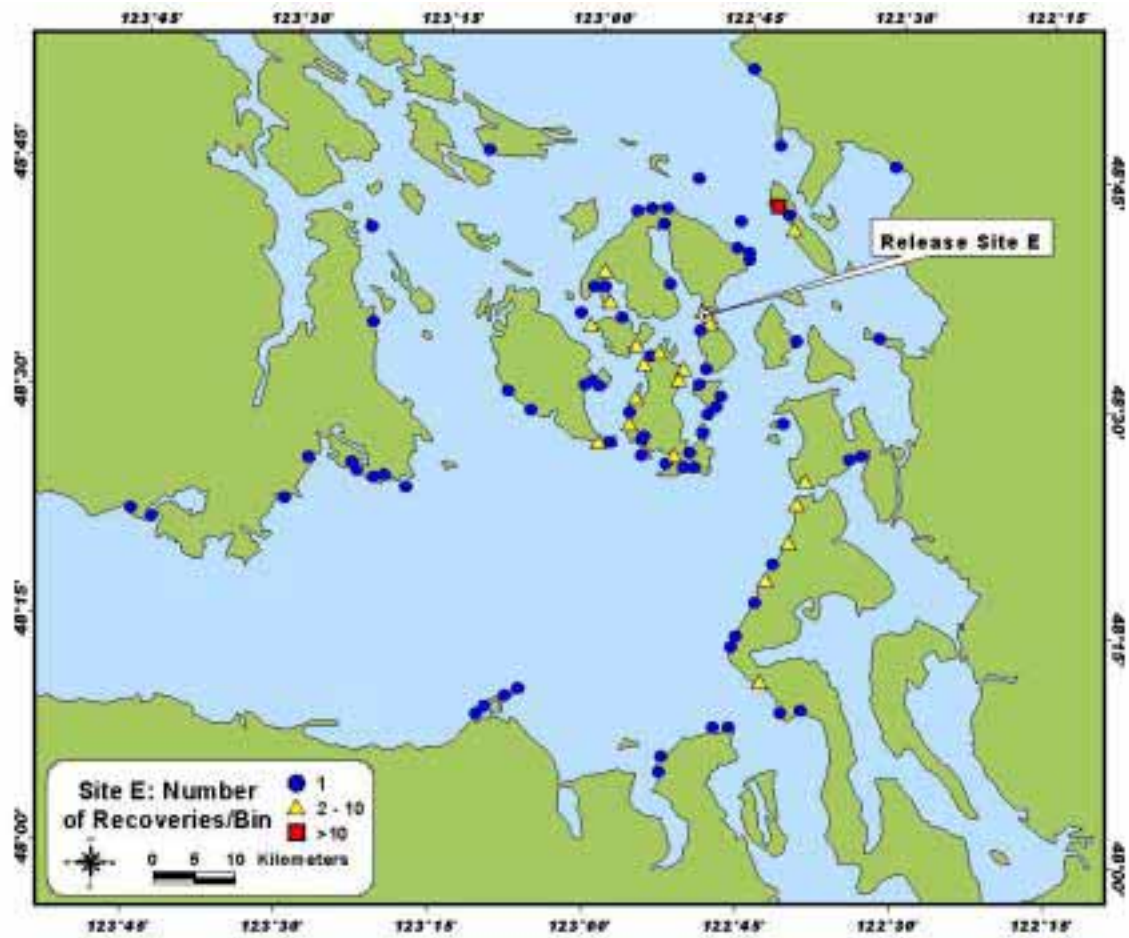


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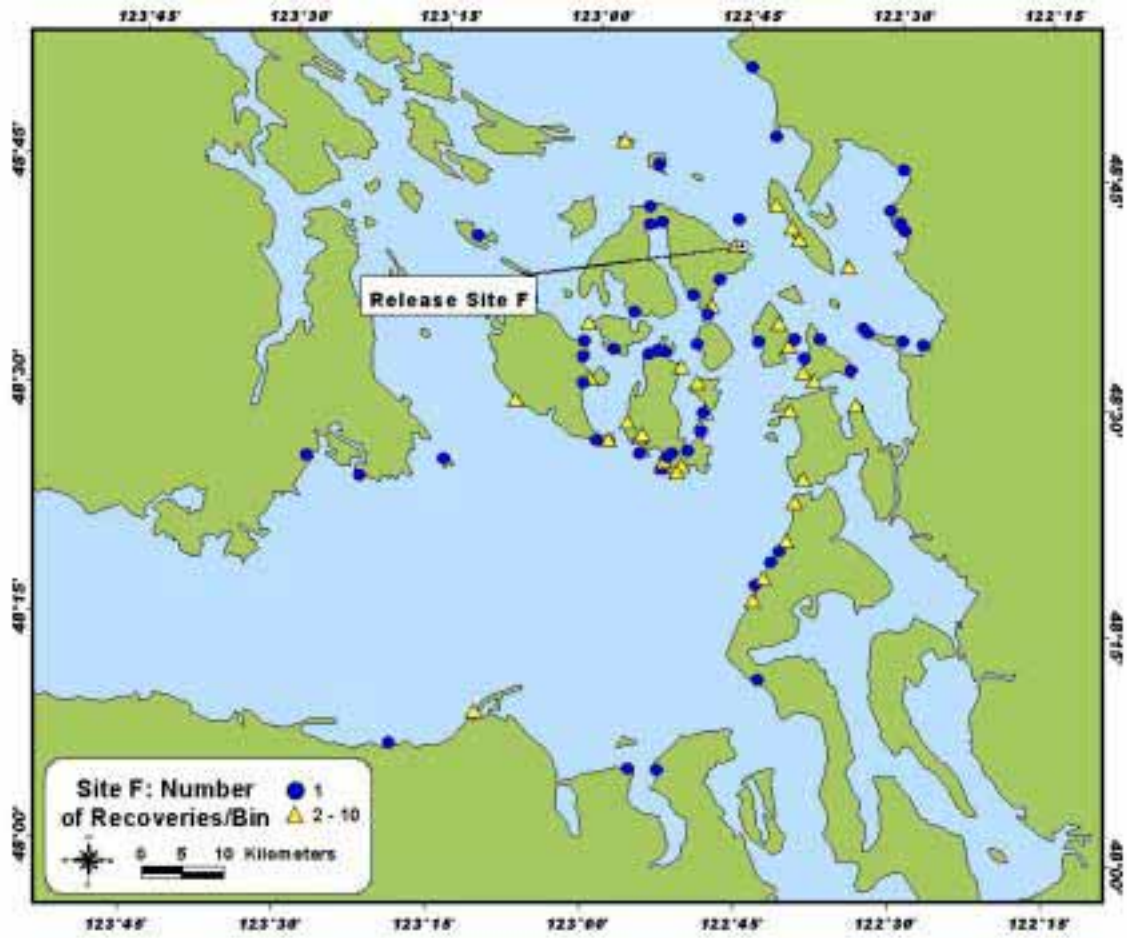


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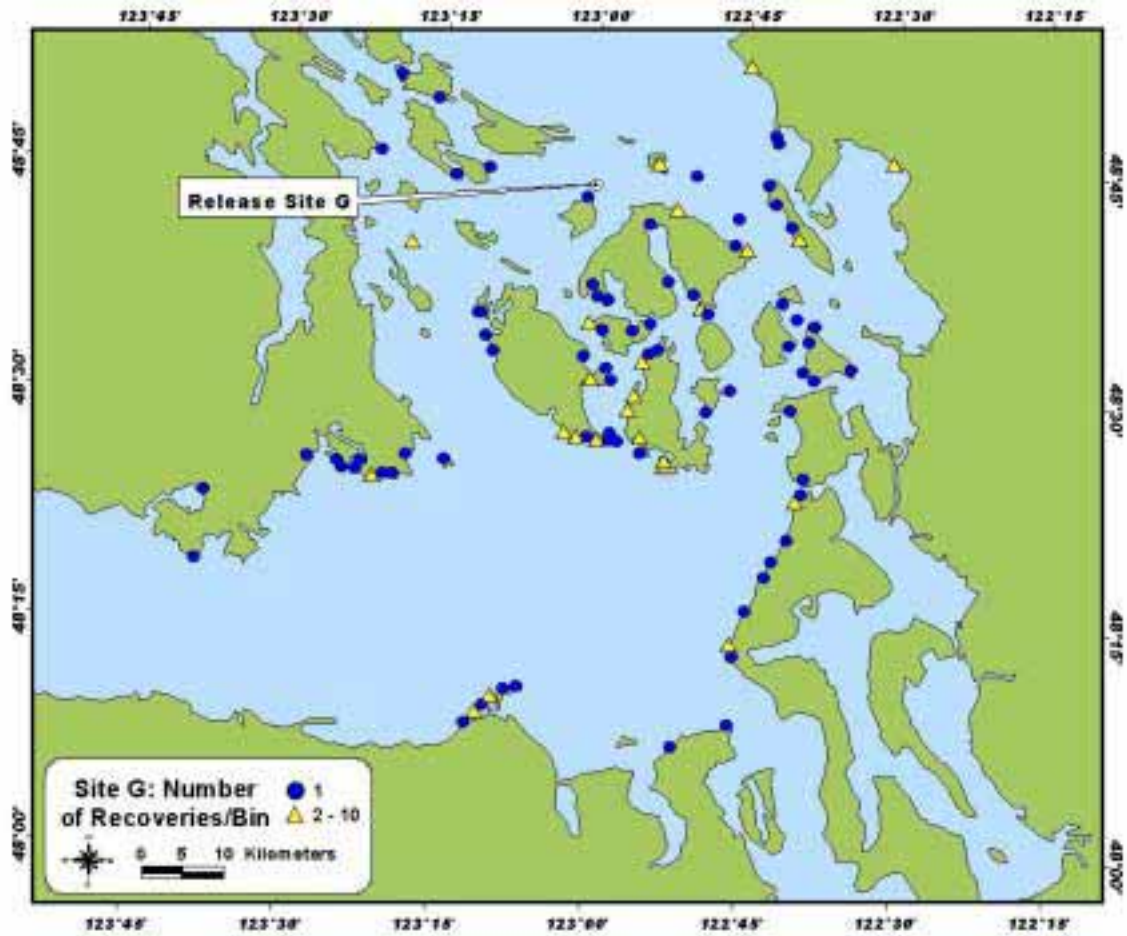


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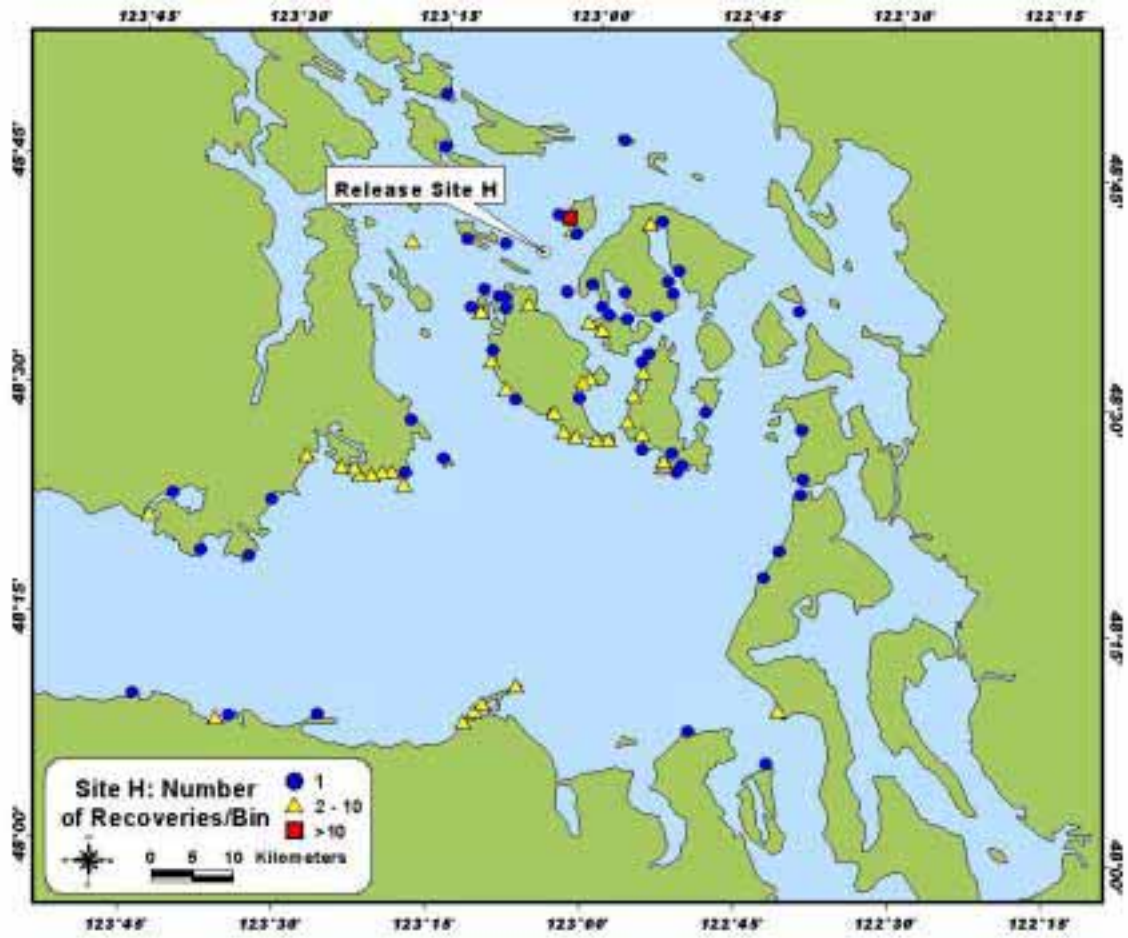


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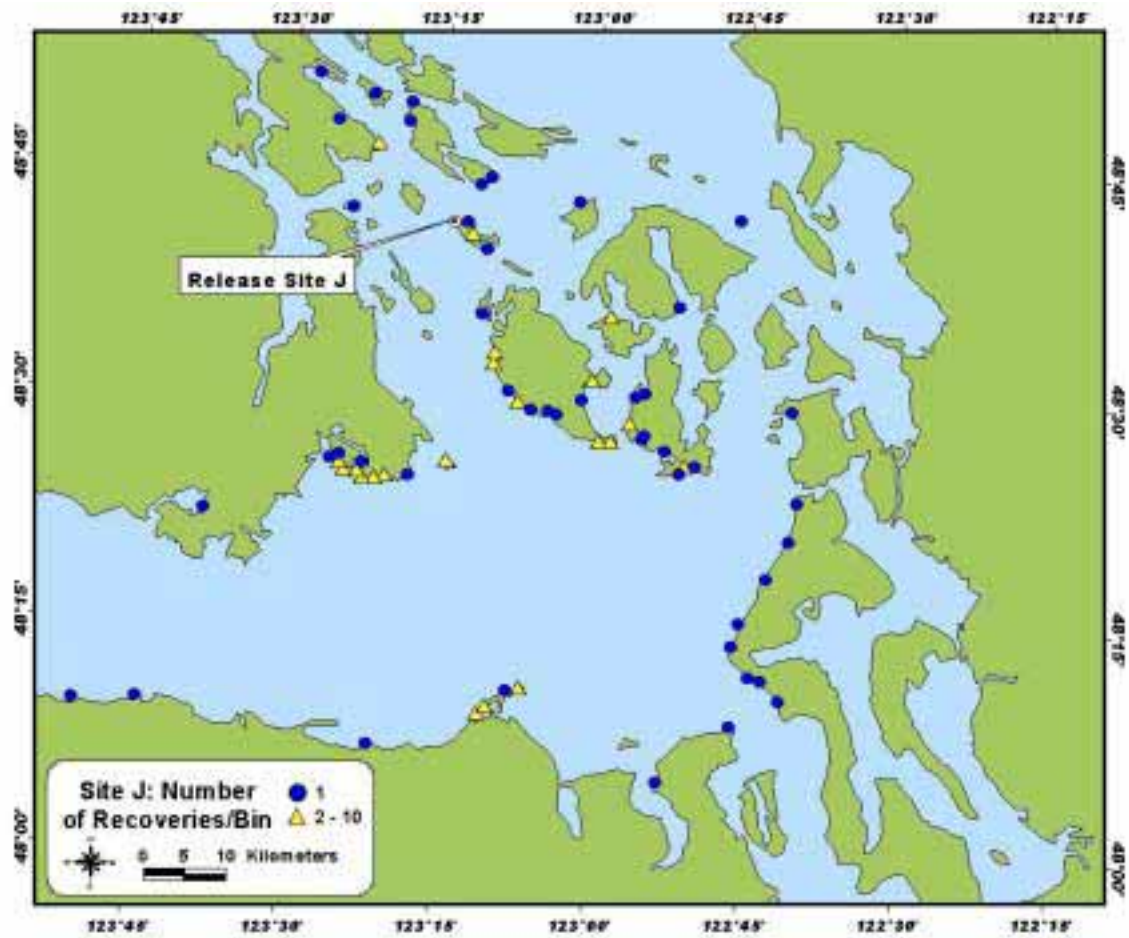


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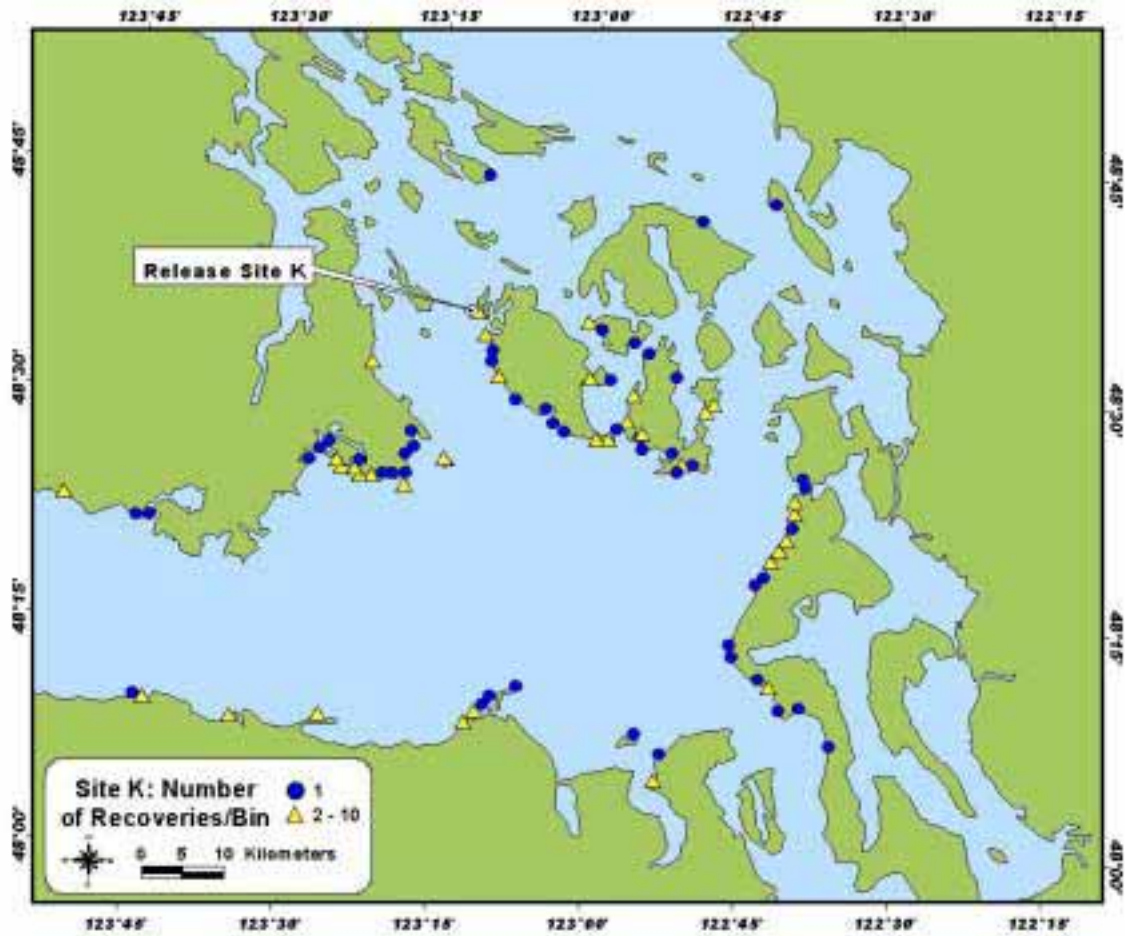


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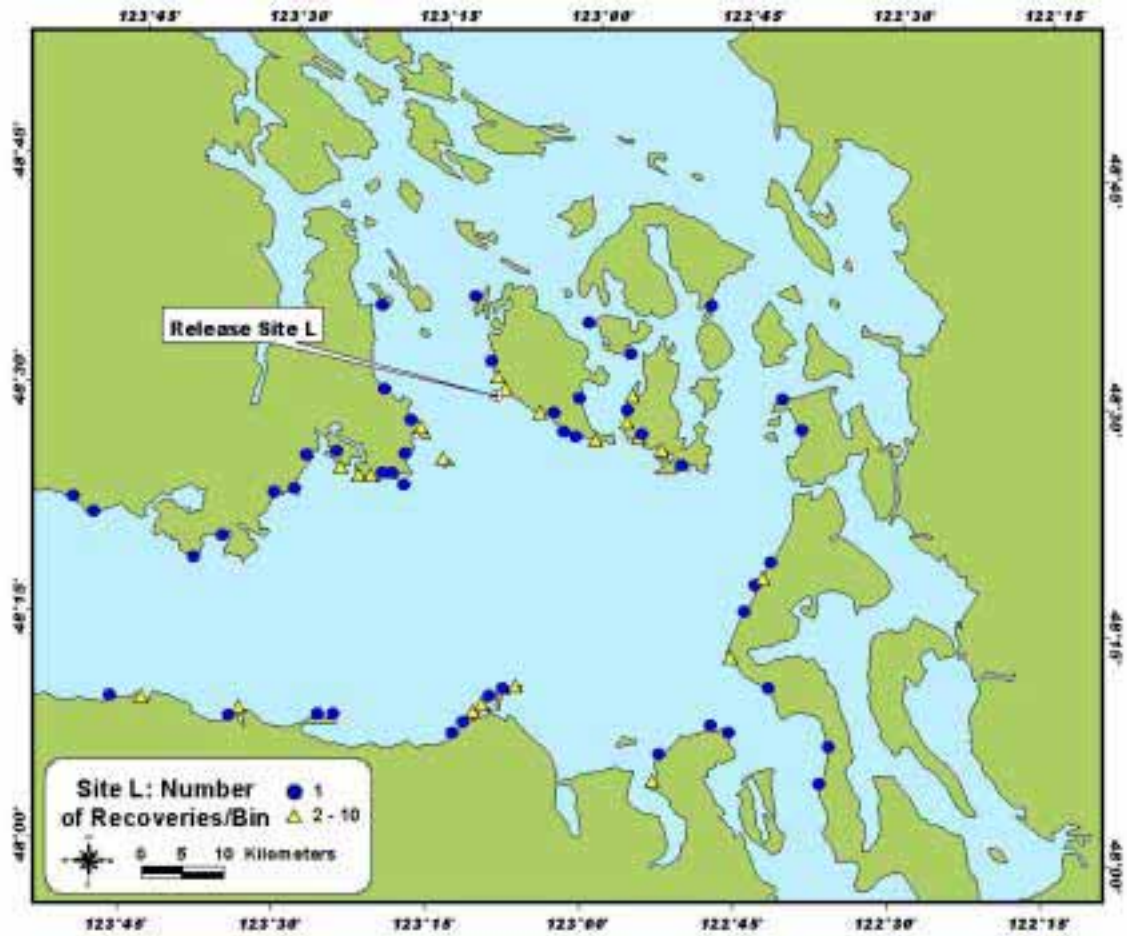


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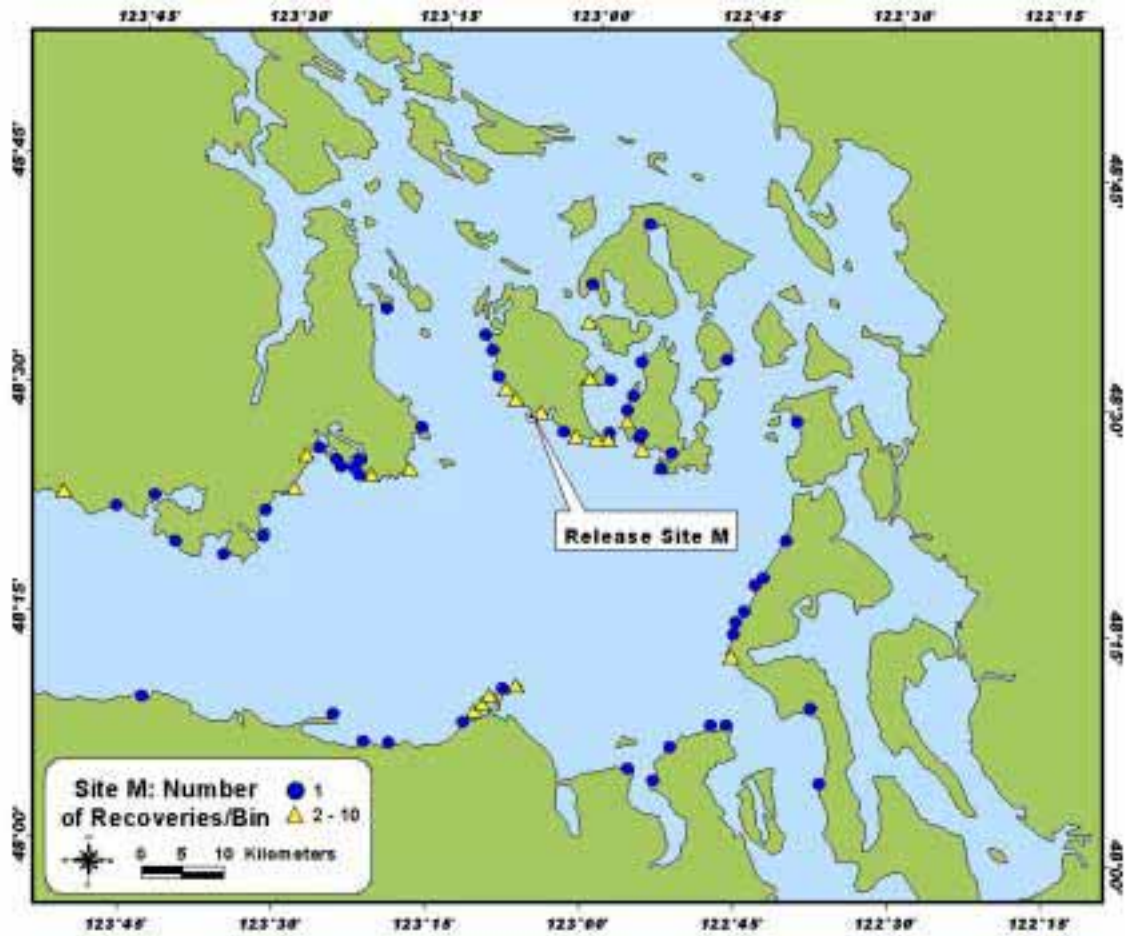


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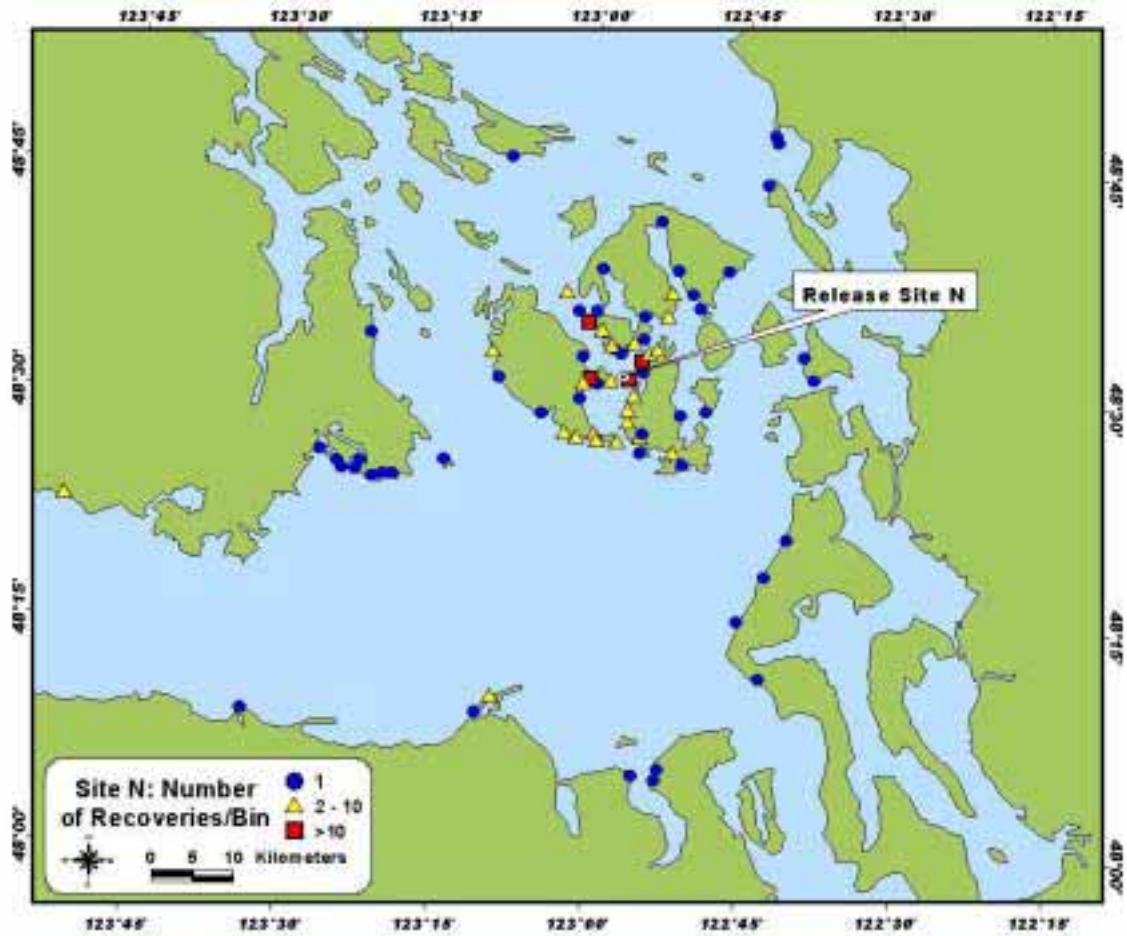


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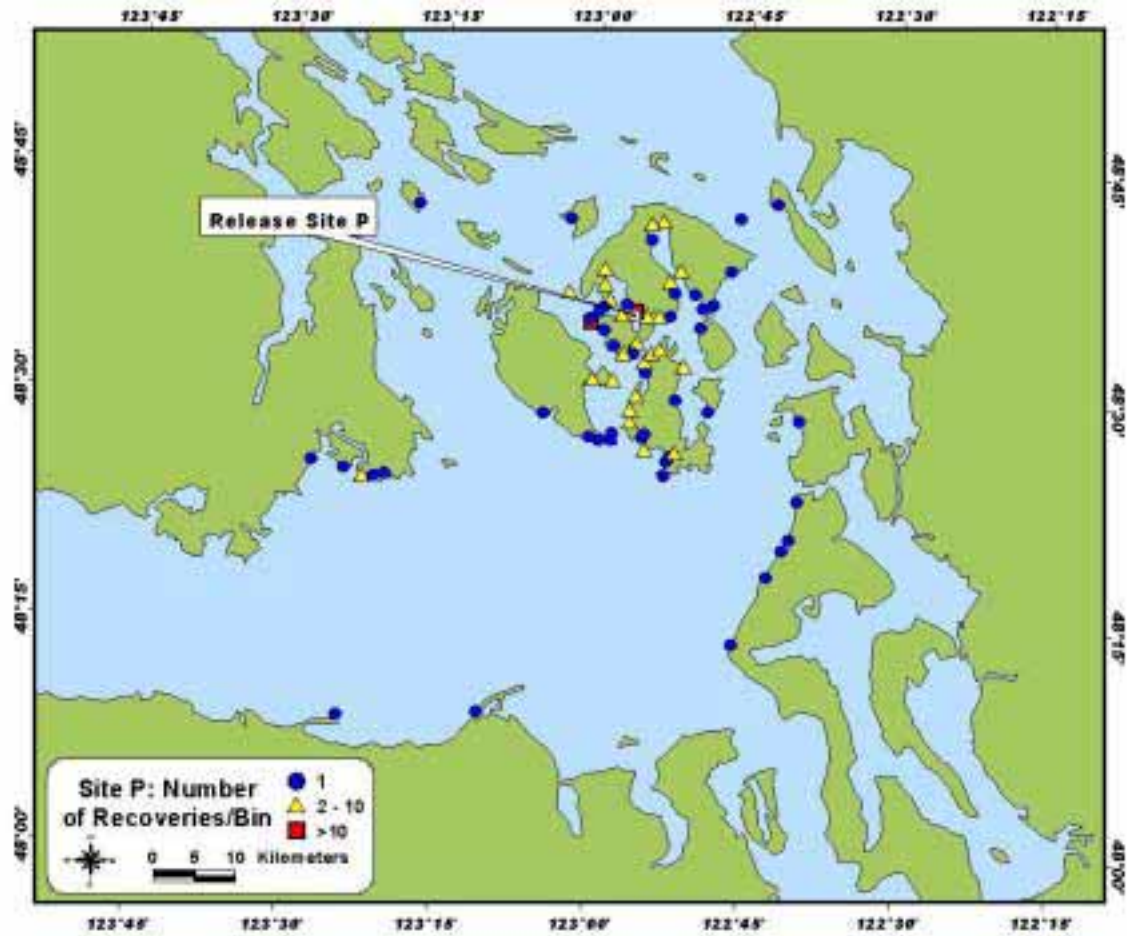


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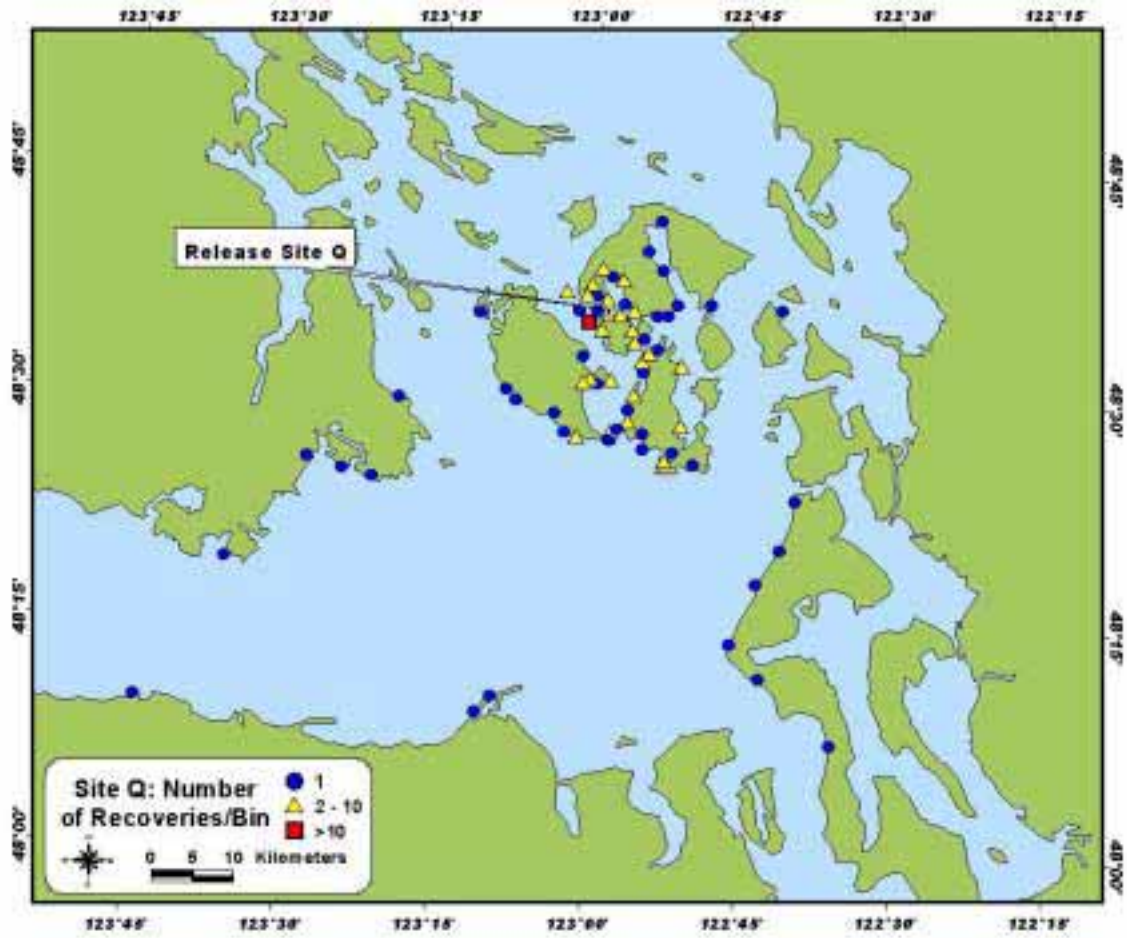


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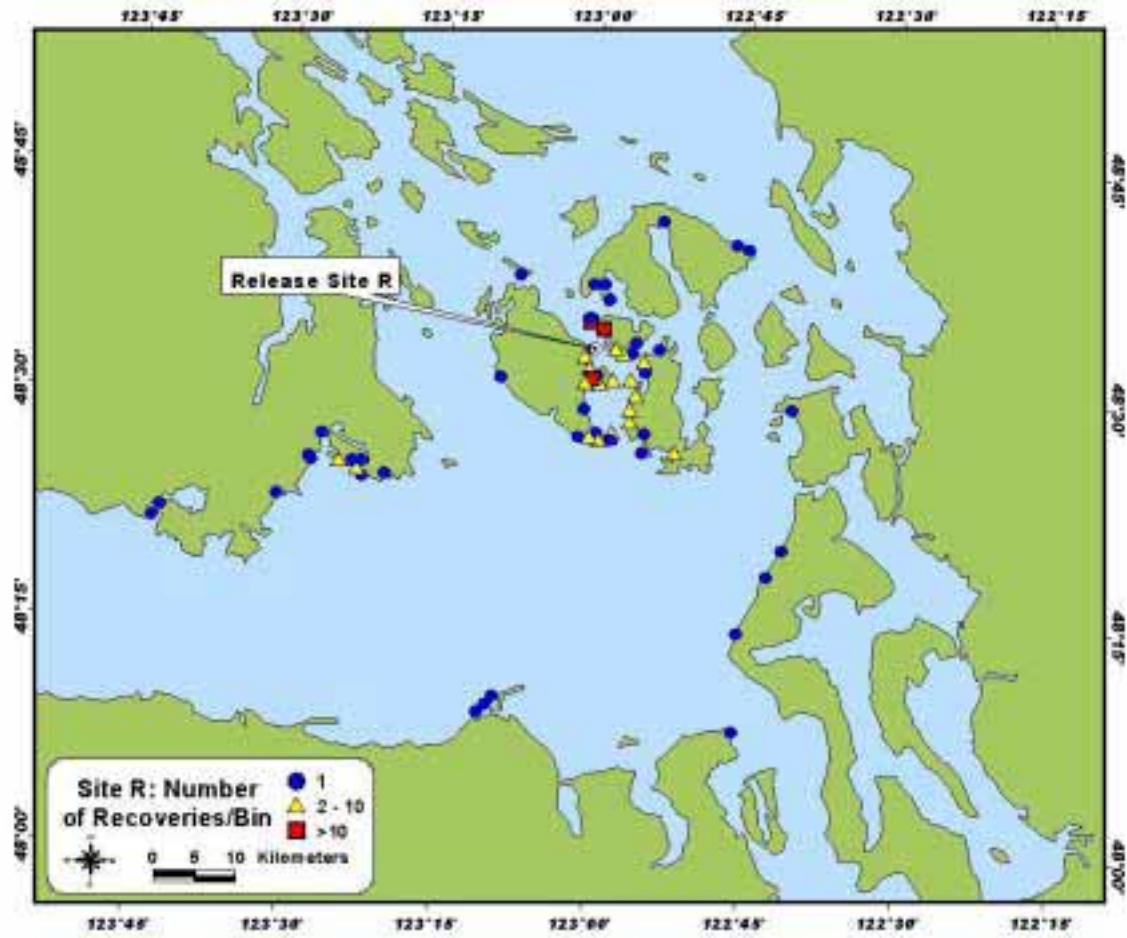


Figure 16.

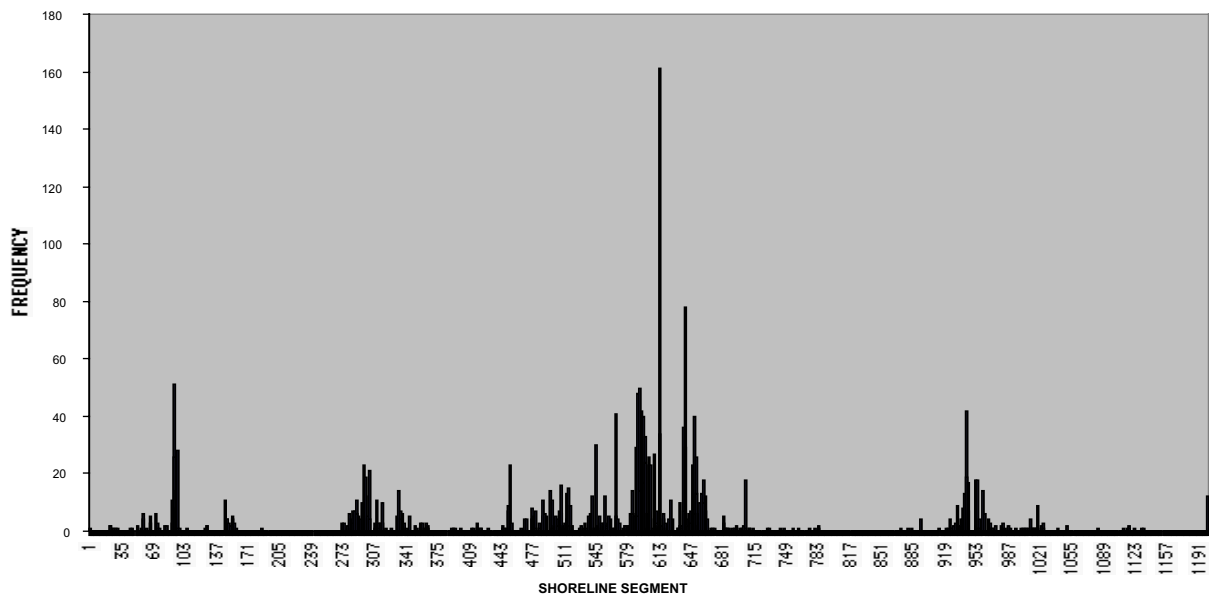


Figure 17. Number of drift cards reported within one-mile shoreline segments. If cards were distributed uniformly, an average of only two cards per segment (i.e., 2,496 cards reported/ 1,197 segments) would be expected. Some segments accounted for 1-2 orders of magnitude more cards (up to 160 cards/mi) than expected. Areas of disproportionately high accumulations included Dungeness Spit (segments 91-95), the northwest shore of Whidbey (280-300), Neck Point on Shaw Island (613), the southwest shore of Lopez (about 585-595), Cattle Point on San Juan Island (648-650), and Victoria (947-953).